

Formation of Metal-Poor Globular Clusters in Lyman α Emitting Galaxies in the Early Universe

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ABSTRACT

The size, mass, luminosity, and space density of Lyman- α emitting (LAE) galaxies observed at intermediate to high redshift agree with expectations for the properties of galaxies that formed metal-poor halo globular clusters (GCs). The low metallicity of these clusters is the result of their formation in low-mass galaxies. Metal-poor GCs could enter spiral galaxies along with their dwarf galaxy hosts, unlike metal-rich GCs which form in the spirals themselves. Considering an initial GC mass larger than the current mass to account for multiple stellar populations, and considering the additional clusters that are likely to form with massive clusters, we estimate that each GC with a mass today greater than $2 \times 10^5 M_\odot$ was likely to have formed among a total stellar mass $\gtrsim 3 \times 10^7 M_\odot$, a molecular mass $\gtrsim 10^9 M_\odot$, and 10^7 to $10^9 M_\odot$ of older stars, depending on the relative gas fraction. The star formation rate would have been several $M_\odot \text{ yr}^{-1}$ lasting for $\sim 10^7$ yrs, and the Lyman- α luminosity would have been $\gtrsim 10^{42} \text{ erg s}^{-1}$. Integrating the LAE galaxy luminosity function above this minimum, considering the average escape probability for Ly α photons (25%), and then dividing by the probability that a dwarf galaxy is observed in the LAE phase (0.4%), we find agreement between the co-moving space density of LAEs and the average space density of metal-poor globular clusters today. The local galaxy WLM, with its early starburst and old GC, could be an LAE remnant that did not get into a galaxy halo because of its remote location.

Subject headings: Galaxies: dwarf — Galaxies: star clusters — Galaxies: star formation — globular clusters: general

1. Introduction

Metal-poor globular clusters (GCs) that inhabit the halos of spiral galaxies (Brodie & Strader 2006) could have arrived there in dwarf galaxies that got captured by dynamical friction and dispersed by tidal forces (Searle & Zinn 1978; Zinnecker et al. 1988; Freeman 1993). Many GCs are still in debris streams (Da Costa & Armandroff 1995; Palma et al. 2002; Mackey & Gilmore 2004; Carraro et al. 2007; Casetti-Dinescu, et al. 2009; Newberg et al. 2009; Mackey et al. 2010) or share orbits with other GCs that presumably came from the same dwarfs (Gao et al. 2007; Smith et al. 2009). The low metal abundance of halo GCs compared with disk and bulge GCs (Strader et al. 2007; Alves-Brito et al. 2011) could then be the result of the mass-metallicity relation for galaxies (Chies-Santos et al. 2011), which is established early on (Erb et al. 2006; Maiolino et al. 2008; Mannucci et al. 2009). A mass-metallicity relation is also present for GCs themselves (Wehner et al. 2008; Forbes et al. 2010; Mieske et al. 2010), although self-enrichment may be the reason (Bailin & Harris 2009). The most heterogeneous GCs could have been dwarf galaxy nuclei (e.g., Bekki & Norris 2006; Carretta et al. 2010).

Metal-poor GCs in elliptical galaxies would have formed in the same types of dwarfs as metal-poor GCs in spirals. Some of these GCs got into the ellipticals after two or more spirals merged (Ashman & Zepf 1992), while others got in with captured dwarfs after the ellipticals formed (Côté et al. 1998). Debris streams containing GCs are observed in ellipticals too (Romanowsky et al. 2012). The larger radial distribution of metal-poor GCs compared with metal-rich GCs in ellipticals (Harris 2009; Forbes et al. 2011; Liu et al. 2011; Faifer et al. 2011) presumably results from this difference in their formation sites.

Metal-rich GCs have a different distribution than metal-poor GCs in spiral galaxies, suggesting that they formed in the disks and bulges of these galaxies along with the other disk stars (Larson 1988), perhaps during a clumpy phase (Shapiro et al. 2010) when the thick disk and bulge formed (Beasley et al. 2002; Griffen et al. 2010; Bournaud et al. 2009). Their higher metallicities result from the generally higher metallicities of their more massive hosts. Metal-rich GCs also get into ellipticals during the mergers of spirals, and other metal-rich GCs form in ellipticals during the merger itself (Ashman & Zepf 1992). Ellipticals then have a higher specific frequency of metal-rich GCs than spirals (Harris 1991) because of the additional GCs that formed during the merger. Ellipticals should also have a higher specific frequency of metal-poor GCs if their more central locations in dense galaxy clusters gave them better access to a rich population of remnant GCs in cluster dwarfs.

The mass distribution functions of metal-poor and metal-rich GCs are about the same (Wehner et al. 2008). Both have a peaked shape with the same characteristic mass ($\sim 2 \times 10^5 M_\odot$). In the dwarf model for metal-poor GCs, this similarity requires that the com-

binned mass distribution of small numbers of clusters from many dwarf galaxies is the same as the single mass distribution of many clusters in a large galaxy. Observations confirm this similarity for old massive clusters in local dwarf and spiral galaxies (Kruijssen & Cooper 2012). The mass function of clusters is apparently a local property of star formation independent of the number of clusters formed (Elmegreen & Efremov 1997). The change from an initial power law or Schechter mass function to a peaked function is presumably the result of selective disruption of low mass clusters shortly after birth (e.g., Parmentier & Gilmore 2005; Elmegreen 2010) and a stellar evaporation rate that is a weak function of cluster mass (McLaughlin & Fall 2008).

Here we consider the formation conditions for GCs in modern environments (Sect. 2) and assess whether metal-poor GCs are likely to have formed in galaxies that have already been observed at high redshift (Sect. 3). The most likely candidates are small active galaxies like Lyman α emitters (LAE). Earlier attempts to link GC formation with specific galaxies or types of galaxies (e.g., Larson 1988) lacked the extensive data on high-redshift star formation that are now available in large surveys. A comparison with other models is in Section 4.

2. Conditions for GC Formation in the Local Universe

In the solar neighborhood of the Milky Way, star clusters form in the midst of other clusters and unbound stars, with a mass that is at most a few percent of the associated molecular cloud mass. One of the nearest regions where star formation has produced a total stellar mass comparable to that in a globular cluster is Eta Carina, where instead of a single cluster there are hundreds of clusters up to $\sim 10^3 M_\odot$ in mass and about three times as much mass in free stars (Feigelson et al. 2011). A bigger star-forming region is W31 at a distance of 6 kpc, which emits $6 \times 10^6 L_\odot$ of young star radiation, contains several ultra-compact HII regions and subclumps of $\sim 10^{5.8} L_\odot$ each, masers and infrared prestellar clumps. The dense molecular clumps, however, extend up in mass to only $\sim 8000 M_\odot$ because they are part of an $dn(M)/dM \propto M^{-1.5}$ power law of clump masses that distributes the total molecular mass of $1.2 \times 10^5 M_\odot$ among smaller pieces (Beuther et al. 2011). The largest cluster likely to come from such clumps is only several thousand M_\odot .

Looking for even larger regions in the Milky Way, one of the most extreme is W43, located at the near tip of the main stellar bar. Such bar-end regions typically house prodigious star formation, presumably because of the massive collection of gas in orbit around the bar (Kenney & Lord 1991). W43 extends for 310 pc and contains a molecular mass of $7 \times 10^6 M_\odot$ in addition to an atomic mass of $3 - 6 \times 10^6 M_\odot$ (Luong et al. 2011). The fraction of molecules in dense ^{13}CO substructures is high, $\sim 10\%$, and the CO line FWHM

is large, 22 km s^{-1} . This is the type of region that might produce a $10^5 M_\odot$ cluster along with many smaller clusters (Luong et al. 2011). It took the Milky Way bar to make these conditions, which means a total distance for gas collection and compression in the bar flow exceeding several kiloparsecs.

For a power law cluster mass function, $dn(M)/dM = n_0 M^{-\beta}$, the ratio of the total cluster mass to the largest cluster mass is

$$\frac{M_{\text{total}}}{M_{\text{max}}} = 1 + \frac{\int_{M_{\text{min}}}^{M_{\text{max}}} M^{1-\beta} dM}{M_{\text{max}} \int_{M_{\text{max}}}^{\infty} M^{-\beta} dM} \quad (1)$$

for minimum cluster mass M_{min} . This ratio implies that the minimum likely young stellar mass to form a single largest cluster of mass M is

$$M_{\text{total}} = \eta_c^{-1} M + \eta_c^{-1} (\beta - 1) M^{\beta-1} \left(\frac{M^{2-\beta} - M_{\text{min}}^{2-\beta}}{2 - \beta}, \ln \left[\frac{M}{M_{\text{min}}} \right] \right), \quad (2)$$

where η_c is the fraction of young stellar mass that forms in bound clusters as opposed to the field, and the second result is for $\beta = 2$. Observations of Eta Carina by Feigelson et al. (2011) suggest $\eta \sim 0.25$. For typical $\beta \sim 2$ and minimum cluster mass $M_{\text{min}} \sim 10 M_\odot$, the minimum total young stellar mass to form a $10^6 M_\odot$ cluster is $5 \times 10^7 M_\odot$. With an average star formation efficiency in molecular clouds of $\sim 2\%$, the associated molecular mass has to exceed $2.5 \times 10^9 M_\odot$. We view this as the necessary molecular mass in a whole galaxy, since by statistical arguments, subclumps that form individual clusters need not all occur in the same shielding envelope for H_2 formation. Similar discussions leading to a large total molecular mass for GC formation were made by Larson (1988) and Harris & Pudritz (1994).

For typical gas fractions of 50% or more at high redshift, as determined from CO observations or star formation rates converted to gas mass using the Kennicutt (1998) relation (Mannucci et al. 2009; Daddi et al. 2010; Tacconi et al. 2010), this result for gas mass implies that the stellar mass in a galaxy that forms a single $\sim 10^6 M_\odot$ GC plus all of the other clusters and bare stars that accompany it in the starburst is typically around $10^9 M_\odot$. For 90% gas fractions at the low metallicities of GCs (Fig. 8 in Mannucci et al. 2009), the underlying stellar mass might be $\sim 10^8 M_\odot$. Lower mass clusters would generally be associated with lower masses of peripheral stars, and the peripheral mass would be lower still if the GC forms in the first galaxy starburst (100% gas fraction).

An upper mass cutoff for clusters giving a Schechter distribution function for mass (i.e., a power law with an exponential tail – Schechter 1976) instead of a power law has been suggested for spiral galaxies by Gieles et al. (2006a,b) and Larsen (2009) and for elliptical galaxies by Waters et al. (2006) and Jordan et al. (2007). Larsen (2009) measured an average

cutoff (where the exponential tail begins) for several spirals at $\sim 2 \times 10^5 M_\odot$. Such a cutoff can increase the required cloud mass if the maximum cluster mass in a distribution is larger than the cutoff mass. Cutoffs have not been explained theoretically except for a possible connection with interstellar pressure (Elmegreen & Elmegreen 2001). The application of such a cutoff to the present problem is uncertain because massive young clusters with $M \sim 10^6 M_\odot$ are observed in dwarf galaxies like NGC 1569 (Ho & Filippenko 1996) and NGC 1705 (Meurer et al. 1995); there is no observation of a statistically significant cutoff in dwarfs.

The star formation rate for a molecular mass of $2 \times 10^9 M_\odot$ is $\sim 1 M_\odot \text{ yr}^{-1}$ for a conventional molecular consumption time of 2 Gyrs (Bigiel et al. 2008; Leroy et al. 2008). This is the characteristic rate for a spiral galaxy today, and large for a dwarf galaxy. If the molecular consumption time was shorter by a factor of ~ 4 in the early universe (Genzel et al. 2010), then a dwarf at that time would have had a very intense starburst, possibly enough to disturb the ISM to a significant degree (e.g. Dekel & Silk 1986; Finkelstein et al. 2011a; McLinden et al. 2011).

We are interested here in whether such a star-forming dwarf could be observed at about the time when it forms a $10^6 M_\odot$ cluster. For a star formation rate of $4 M_\odot \text{ yr}^{-1}$ lasting $\sim 100 \text{ Myr}$, which is the orbit time of a 0.5 kpc radius disk with a typical dwarf galaxy rotation speed of 30 km s^{-1} , the SDSS g-band absolute AB magnitude would be -20.0 and the young-star luminosity $1 \times 10^{10} L_\odot$ (according to models in Bruzual & Charlot 2003 for a metallicity of 0.2 solar; emission lines would make the galaxies brighter). For redshifts $z = 2$ and $z = 6$, where the distance moduli in the observer frame are 46.0 and 48.9 and the restframe g-band shifts to $1.4\mu\text{m}$ and $3.3\mu\text{m}$, the apparent AB magnitudes would be 26.0 and 28.9, respectively. These magnitudes are bright enough to be detected in deep surveys. Similarly, the absolute g-band AB magnitude of a model cluster 100 Myr old with $10^6 M_\odot$ at birth can be determined from Bruzual & Charlot (2003) to be -12.46 . At $z = 2$ and 6, the apparent magnitudes of such a cluster would be 33.5 and 36.4 mag, which are beyond the current limits.

Also related to observability is the diameter of a typical dwarf galaxy, $\sim 1 \text{ kpc}$, which corresponds to an angular size of 0.12 arcsec at $z = 2$ and 0.17 arcsec at $z = 6$. These sizes can be resolved by HST and some ground-based instruments with adaptive optics, which implies that the formation environments for metal-poor GCs can be observed directly. The $10^6 M_\odot$ clusters themselves would not be resolved, however.

The co-moving space density of dwarf galaxies that formed GCs during an intense starburst should have been about twice the space density of metal-poor GCs today, considering one forming GC per dwarf and an evaporative loss of about a factor of 2 during the intervening time (Vesperini 1998). The space density of all GCs today is ~ 8

Mpc^{-3} (Portegies Zwart & McMillan 2000), of which about half to two-thirds are metal-poor (Forbes et al. 2000), i.e., the blue GCs in the bimodal color distribution. This makes the expected dwarf galaxy co-moving density at the time of metal-poor GC formation equal to about 8 Mpc^{-3} , although only one quarter of these produce GCs more massive than the peak in today’s GC mass function. We discuss these densities in more detail below.

The metallicities of metal-poor GCs should be about the same as the gas metallicities of the galaxies they formed in, which is low for low-mass galaxies at intermediate to high redshift. Zinn (1985) considered that metal poor halo GCs have $[\text{Fe}/\text{H}] < -0.8$ and Muratov & Gnedin (2010) considered $[\text{Fe}/\text{H}] < -1$. If we consider the solar abundance to be $12 + \log(\text{O}/\text{H}) = 8.66$ (Asplund et al. 2004), then metal-poor GCs have $12 + \log(\text{O}/\text{H}) < 7.7$ or 7.8. This value is consistent with the observed gas metallicities of galaxies with stellar masses less than $10^9 M_\odot$ and redshifts greater than $z \sim 3.5$ (Maiolino et al. 2008; Mannucci et al. 2009).

The local galaxy WLM, at a distance of $\sim 1 \text{ Mpc}$ (McConnachie et al. 2005), is an example of a dwarf with a metal-poor GC and a very early starburst of about the same age. According to Dolphin (2000), the galaxy has an iron abundance that rises from $[\text{Fe}/\text{H}] = -2.18 \pm 0.28$ to -1.34 ± 0.14 in a prolonged starburst that occurred 12 Gyr to 9 Gyr ago, and it has a globular cluster (Ables & Ables 1977) with an abundance of $[\text{Fe}/\text{H}] = -1.63 \pm 0.14$ (from Hodge et al. 1999) that also has a very old age, estimated to be ~ 14 Gyr by Hodge et al. (1999). Enhanced α elements in the GC suggest a period of rapid star formation in the gas from which it formed (Colucci & Bernstein 2011). Most of the WLM halo stars are also very old (Minniti & Zijlstra 1997). The stellar mass of WLM today is $\sim 1.6 \times 10^7 M_\odot$ (Zhang et al. 2012); the total dynamical mass within the half-light radius of 1.6 kpc is $4.3 \pm 0.3 \times 10^8 M_\odot$ (Leaman et al. 2012). The V-band absolute magnitude of the GC is -8.8 mag (Sandage & Carlson 1985; Hodge et al. 1999), which gives it a luminosity 4.8 times greater than the luminosity at the peak of the Milky Way globular cluster distribution function. Scaling the GC mass accordingly makes it $10^6 M_\odot$, or 10% of the current galaxy stellar mass. Leaman et al. (2012) suggest that the WLM stellar mass was only $8 \times 10^5 M_\odot$ 11 Gyr ago, which is comparable to the GC mass at the same time. Evidently, the GC in WLM was the dominant part of a major starburst shortly after the galaxy formed. It remains inside WLM and not in the halo of the Milky Way or M31 because of its large distance from both, $\sim 1 \text{ Mpc}$ (Leaman et al. 2012). We propose that most of the other metal-poor GCs that formed in young dwarfs in the local group got captured by the Milky Way, M31, or M33, or possibly also by the LMC and SMC, before the rest of the dwarf galaxy gas had a chance to form more stars like WLM did. Thus the remnant streams may have low stellar masses like WLM did when it formed its GC; this is much less than the stellar mass in WLM today.

In summary, a wide variety of evidence points to the formation of metal-poor globular clusters in low mass galaxies at intermediate to high redshift. Simple considerations suggest that such galaxies could be observed with modern instruments during their GC-formation phase, although the young GCs themselves probably cannot be distinguished. We ask now whether the active phases of the host galaxies have been observed already.

3. Lyman α Emitters as Sites for GC Formation

Small, metal-poor galaxies at high redshift are a natural choice for the birth place of metal-poor globular-clusters. Lyman- α emitting galaxies are typically dwarf star-forming galaxies at intermediate to high redshift. Most LAE galaxies have low stellar masses, typically between 10^7 and $10^8 M_\odot$ (Pirzkal et al. 2007; Finkelstein et al. 2007), although a small fraction have higher mass following a Schechter luminosity function (Lai et al. 2007; Finkelstein et al. 2008, 2009). The Lyman α emitting regions in LAE galaxies are usually very young, with stellar ages of a few 10^7 yrs (Pirzkal et al. 2007; Gawiser et al. 2007; Finkelstein et al. 2007, 2008, 2009). Sometimes there is an older underlying population of stars too (Nilsson et al. 2011; Acquaviva et al. 2012). LAEs are usually compact (\sim kpc; Pentericci et al. 2009; Bond et al. 2009, 2010; Finkelstein et al. 2011b), with a characteristic radius that does not evolve much with redshift (Malhotra et al. 2012), although the LAEs with underlying populations could be growing in mass (Nilsson et al. 2011). This paradigm explains the number densities of LAE galaxies as well as their clustering statistics (Kovač et al. 2007; Gawiser et al. 2007; Tilvi et al. 2009). LAEs are also seen to be metal poor (~ 0.1 solar; Finkelstein et al. 2011a; Richardson et al. 2012, in prep).

LAE galaxy properties can be explained by postulating that most of them are dwarf galaxies emitting Lyman- α in the first $\sim 3 \times 10^7$ years after a major starburst (Malhotra & Rhoads 2002). The escape of Lyman α radiation would favor a porous interstellar medium in a small galaxy, so there may be a selection effect for dwarfs among LAE samples. This selection works in our favor because we are looking for dwarfs that had starbursts at intermediate to high redshift. We postulate that these dwarfs are the formation sites of metal-poor GCs, and the precursors of the remaining stellar streams that accompanied these GCs into galaxy halos. Extreme emission line objects at intermediate redshift are in the same category, and with their enormous starbursts, could have made most of today’s dwarfs (van der Wel et al. 2011).

Can LAEs produce most of the metal-poor GCs seen at the present time? The mass function of GCs today is a log-normal distribution centered at $\sim 2 \times 10^5 M_\odot$ (McLaughlin 2003). These clusters have lost some of their original mass by evaporation. McLaughlin & Fall

(2008) fit the current GC mass function with an initial Schechter function and an evaporated mass per cluster of $\Delta = 1.45 \times 10^4 M_\odot (\rho_h / M_\odot \text{ pc}^{-3})^{1/2}$ for cluster density $\rho_h \sim 10 - 1000 M_\odot \text{ pc}^{-3}$ inside the half-light radius. For average $\rho_h = 246 M_\odot \text{ pc}^{-3}$ in the Milky Way, $\Delta = 2.3 \times 10^5 M_\odot$ (McLaughlin & Fall 2008). The initial GC mass would have been at least this much larger than its current mass.

We estimated above that the number density of original metal-poor clusters had to be about $\sim 8 \text{ Mpc}^{-3}$. This came from a current density of $\sim 4 \text{ Mpc}^{-3}$, multiplied by 2 to account for evaporation. For a nearly constant evaporation rate per cluster, this estimate of initial density should be done again, now in two parts. First, we consider all clusters with a mass today larger than $2 \times 10^5 M_\odot$, which is both the mass at the peak of the GC mass function and the total evaporated mass per cluster, on average. An approximation is that all clusters originally larger than this are still present today because they have not completely evaporated yet. Their density is about half the current density of metal-poor GCs, giving $\sim 2 \text{ Mpc}^{-3}$, because they represent half of the current GC mass function by number. Thus we ask whether galaxies going through the LAE phase and forming clusters more massive than $2 \times 10^5 M_\odot$ today had a co-moving space density of around 2 Mpc^{-3} .

Second, we consider lower mass clusters. These are on the low-mass, decreasing part of the current GC mass function and should be highly evaporated from their initial state. The mass function of clusters at birth is usually observed to be $dn(M)/dM \propto M^{-2}$ (e.g., de Grijs & Anders 2006; Larsen 2009). If we consider as representative the lower part of the GC mass function down to 1/4 the mass of the peak, then the initial number of clusters below the peak, i.e., between 1/4 and 1 times the current peak, is 3 times the number of clusters with masses greater than the current peak, based on this initial cluster mass function. Presently, there is an equal number of clusters with a mass below and above the peak, so 1/3 of those below the peak survive. The total survival fraction is still the factor of 2 estimated in the introduction, but now we have divided it up between 100% survival at $M > 2 \times 10^5 M_\odot$ and 33% survival at initial $M < 2 \times 10^5 M_\odot$. (That is, for every GC today at $M > 2 \times 10^5 M_\odot$ there was one GC originally, and for every GC today at $M < 2 \times 10^5 M_\odot$ there were three GCs originally). We first check whether clusters above the current peak could have formed in LAE galaxies.

To make a cluster of mass $2 \times 10^5 M_\odot$ today, the initial stellar mass had to be larger, not only because of evaporation over a Hubble time, as discussed above, but also to account for the high abundance of elements from first-generation stellar ejecta that are present in second-generation stars. Globular clusters have multiple stellar populations (see reviews in Renzini 2008; Carretta et al. 2010b). Models by D’Ercole et al. (2008, 2012), Bekki (2011), Schaerer & Charbonnel (2011) and others suggest that the initial cluster mass was $\sim 10^6 M_\odot$.

or more, ten times larger than the present day mass. These models are uncertain, but to be consistent with them, we assume that the initial characteristic cluster had $2 \times 10^6 M_\odot$. It would most likely have been accompanied by other clusters, making the total young stellar mass $\sim 3 \times 10^7 M_\odot$ if $\eta = 1$ in equation (2). Most of the star formation that made these clusters, whether in the first or the second generations, would presumably occur in $\sim 10^7$ years, before supernovae could remove the star-forming gas (D’Ercole et al. 2012). However, the total span of cluster formation could have taken ~ 100 Myr, considering the need for enriched ejecta from first-generation stars to re-accumulate along with fresh material to form the second generation. Non-clustered stars would most likely have been present with the first generation too ($\eta < 1$), but they would presumably be relatively dim by the time the second generation stars formed in the final cluster burst. Considering the many uncertainties that are still present in the detailed theory of GC formation, we use here a representative luminosity for the starburst phase that is equivalent to $3 \times 10^7 M_\odot$ of stars forming in ~ 10 Myr. This gives a star-formation rate during the main starburst equal to $3 M_\odot \text{ yr}^{-1}$.

Another consideration is the absorption by dust of Lyman continuum radiation before it ionizes the nearby gas and produces Lyman α radiation. We assume a small amount, $A_{\text{LC}} \sim 1$ magnitude of extinction for Lyman continuum radiation (e.g., Finkelstein et al. 2011c; Walter et al. 2012). That reduces the effective star formation rate for Lyman α production to $\sim 1 M_\odot \text{ yr}^{-1}$. This implies a Lyman- α line luminosity of $1 \times 10^{42} \text{ erg s}^{-1}$ if the escape fraction of the Lyman- α photons is 100%. Recent studies of LAE galaxies show that the average escape fraction of Lyman- α photons is between 17% and 30% (Blanc et al. 2011; Zheng et al. 2012; Richardson et al. 2012, in prep). Assuming an average escape fraction of 25%, a SFR of $1 M_\odot/\text{year}$ translates into Lyman- α line luminosity of $2.5 \times 10^{41} \text{ erg s}^{-1}$.

Now we integrate the Lyman- α luminosity function (Zheng et al. 2012b) with $\log(L_*) = 42.86 \pm 0.06$ and $\phi_* = -3.55 \pm 0.09$ down to this minimum luminosity of $2.5 \times 10^{41} \text{ erg s}^{-1}$. We assume a slope of -2 at low mass. This gives the number density of Lyman- α galaxies brighter than the cutoff for forming a characteristic GC equal to $7 \times 10^{-3} \text{ Mpc}^{-3}$.

In deriving this density, we have assumed that the Lyman- α phase lasts for 10^7 years, whereas we observe that the Lyman- α luminosity function is essentially unchanged from $z = 2$ to 7, a time interval of 2.56 Gyrs. This duration for the LAE morphology corresponds to ~ 256 generations of individual Lyman- α events, or a probability of catching a low-mass galaxy in the LAE phase equal to 0.39%. Dividing the observed number density of LAE galaxies that can make today’s $M > 2 \times 10^5 M_\odot$ GCs by the probability of observation produces a total number density of such galaxies that go through the LAE phase equal to $\sim 1.9 \text{ Mpc}^{-3}$. If each LAE phase forms a single GC with a present-day mass of $M > 2 \times 10^5 M_\odot$ (along with smaller clusters, as discussed above), then this would be the comoving number

density of metal-poor GCs that end up more massive than the median mass of today’s GCs. This is in fact the initial co-moving density of low-metal, high-mass GCs that we expected from the above discussion of current GC density and evaporation rate. Thus dwarf LAE galaxies at redshifts from 2 to 7 could have formed most of the metal poor GCs observed today in the high-mass half of the GC mass distribution function.

Formation of the low-mass GCs requires a higher space density of lower-luminosity LAEs because there were three times as many initially low-mass GCs as high mass GCs. This result is easily obtained, however, because the LAE luminosity function, presumed equal to the LAE mass function, has the same slope as the initial GC mass function, namely, -2 for equal intervals of mass. Thus there were 3 times as many LAEs between $1/4$ and 1 times the fiducial luminosity estimated above as there were above the fiducial luminosity, just as there were 3 times as many initial GCs below the current peak as above. We conclude that all of the GCs could have been made in LAE galaxies, based these assumptions.

The above estimates can be summarized by two equations:

$$n(M > M_{*,min}) = \frac{T}{t_{LyA}} \int_{L_{min}}^{\infty} \Phi(L) dL = \frac{T}{t_{LyA}} \Phi^* \Gamma(\alpha + 1, L_{min}/L^*) \quad (3)$$

and

$$L_{min} = \frac{M_{*,min}}{t_{LyA}} f_{esc,LyA} 10^{-0.4A_{LC}} \times \frac{10^{42} \text{erg s}^{-1}}{M_{\odot} \text{yr}^{-1}}, \quad (4)$$

where $M_{*,min} \approx 13M_{cl}$ from equation (2) is the minimum stellar mass formed during the starburst lasting for the time t_{LyA} . We assume a luminosity function described by a Schechter function. Our calculation above used fiducial values of $T = 2.56$ Gyrs, $t_{LyA} = 10^7$ yr, $f_{esc,LyA} \sim 0.25$, $A_{LC} \sim 1$, $\log(\Phi^* \times \text{cMpc}^3) \approx -3.55$, $\log(L^*/\text{erg s}^{-1}) \approx 42.86$, $\alpha = -2$, and $M_{cl} \approx 2 \times 10^6 M_{\odot}$.

These equations show that the space density of GCs derived from the LAE luminosity function is insensitive to the lifetime t_{LyA} of the Lyman- α phase. If we assume that the life span of the Lyman- α emitting phase goes up to $t_{LyA} = 3 \times 10^7$ years, then the minimum SFR and the Lyman- α luminosity required would be lower by a factor of three. The number of Lyman- α emitters brighter than this cutoff would increase by roughly a factor of 3. However, the total number of GCs produced over the redshift interval $z = 2$ to 7 would remain the same, since our 2.56 Gyr interval is now only ~ 85 generations of galaxies.

Formal uncertainties in the luminosity function parameters taken from Zheng et al. (2012b) change the final numbers by only about 6%, since the errors in ϕ_* and L_* are anticorrelated and roughly cancel out. There is however a larger spread in the luminosity function parameter found for LAEs by different authors and surveys. Taking two extremes:

(1) Hu et al. (2010) found $\phi_* = -3.96$ and $L_* = 43.0$ at $z=5.7$, which would yield about half of the GC number density calculated above; (2) Ciardullo et al. (2012) found $\phi_* = -2.96$ and $L_* = 42.6$ at $z=3.1$ yielding 2.3 times the number density derived above. A change of slope in the faint end of the luminosity function from $\alpha = -2.0$ to $\alpha = -1.8$ reduces the number of GCs to 60% of the above value. The faint end of the luminosity function is quite steep, however, in both LAEs (Rauch et al. 2008) and Lyman break galaxies (Yan & Windhorst 2004); thus, -2 may be a more reasonable estimate for the slope.

The Lyman- α escape fraction is also uncertain, perhaps by a factor of 1.6 to 2, as is the extinction for Lyman Continuum radiation, A_{LC} , the initial representative cluster mass, M_{cl} , and the fraction of stars formed in clusters, η . A lower escape fraction, higher A_{LC} , lower M_{cl} , or higher η will all lower the observed Lyman- α luminosity from a GC-forming galaxy, and this increases the space density of such galaxies according to the luminosity function. The resulting density of GCs increases in proportion. Lower M_{cl} , as recently proposed by Larsen et al. (2012), can be accompanied by a proportionally lower cluster formation fraction, η , and not change the GC space density much. The formation of more than one GC per LAE galaxy would not increase the space density of GCs, because we are accounting already for all of the luminosity associated with GC formation. If 2 GCs are made in each LAE, then the LAEs would have twice the fiducial luminosity (or each would form a single GC twice as often), and about half the estimated number of LAEs would be forming these GCs. The total number of final GCs remains about the same.

Other small galaxies in the early universe could be formation sites for GCs too, but if these galaxies are not Lyman- α emitters, then they are probably not in the starburst phase at the time of observation, and whatever GCs they formed came about earlier (or may come about later). In that case, they are already counted in the above discussion when we considered the $\sim 0.39\%$ probability for the LAE phase. In addition, some dwarf starburst galaxies that form metal-poor GCs may have low Lyman α escape fractions (e.g. Heckman et al. 2011), placing them below our limit of integration over the luminosity function. These galaxies balance those with high escape fractions, since we use only the average value of 25% here as an estimate for this fraction. More massive galaxies would have formed GCs in starbursts as well, but then the GC metallicities would be larger at the redshifts when typical galaxies became massive, and the result would be metal-rich GCs. This is the likely formation mechanism for metal-rich GCs, which are still correlated with the disk and bulge populations of spiral galaxies (Shapiro et al. 2010).

4. Comparison with other Models

Previous models of GC formation in a cosmological context (e.g., Bromm & Clarke 2002; Beasley et al. 2002; Kravstov & Gnedin 2005; Moore et al. 2006; Bekki et al. 2008; Griffen et al. 2010; Muratov & Gnedin 2010) contain many aspects of the present proposal without identifying likely hosts that could be visible at intermediate to high redshift. Beasley et al. (2002) discussed metal-poor GC formation in gassy disks at early times and suggested that the GC formation sites might be damped Ly α systems, which are gas clouds seen in absorption with high column densities and very low emission from young stars (Rafelski et al. 2011). We suggest that GC formation sites are brighter than this.

A variety of models for triggering GC formation have been considered, such as collisions between dwarf galaxies (Muratov & Gnedin 2010) or pressures from a nearby galaxy (Gray & Scannapieco 2011). Here we discussed GC formation in small galaxies regardless of their proximity to large galaxies and regardless of what triggers the star formation. If LAE galaxies are the formation sites, then any correlation between LAEs and large galaxies in the early universe could reveal the extent to which metal-poor GCs formed in halo sub-clumps versus the field. The observation of isolated LAEs would imply that their metal-poor GCs entered today’s galaxy halos later, presumably making the observed remnant stellar streams by tidal disruption.

Observations show overdensities of LAE galaxies only on the scale of galaxy clusters, namely, $\sim 10^{14} M_{\odot}$ and several Mpc (Kurk et al. 2004; Venemans et al. 2005; Kovač et al. 2007; Gawiser et al. 2007; Tilvi et al. 2009; Overzier et al. 2006, 2008). This cluster overdensity allows centrally-located elliptical galaxies to accrete a higher proportion of metal-poor GCs from former LAEs than spiral galaxies can. Such enhanced accretion is consistent with a greater specific frequency of metal-poor GCs in ellipticals compared to spirals.

For dwarf galaxy hosts in general, metal-poor GCs should form over a range of times because their abundance reflects the metal-poor environment of the dwarf galaxy, rather than the average metallicity of the universe. NGC 1569 (Kobulnicky & Skillman 1997) and NGC 1705 (Lee & Skillman 2004) are examples of moderately metal-poor environments that make massive clusters today. They did not fall into the halos of more massive spiral galaxies, and so their stellar masses and heavy element abundances continued to increase. Other models have been concerned with truncating the formation of GCs after a short formation epoch in order to keep the metallicity low (e.g., Bekki et al. 2008). A key observation will be the age spread of metal-poor GCs. Extended formation times for metal-poor GCs were recently observed for S0 galaxies by Chies-Santos et al. (2011). There was also a suggestion of extended metal-poor GC formation in one of the stellar population fits by Mendel et al. (2007) for Milky Way GCs.

5. Conclusions

Metal-poor GCs could have entered the halos of spiral galaxies in the form of starburst remnants in old dwarf galaxies. Their low metallicities are not the exclusive result of an earlier birth time compared to metal-rich disk and bulge GCs, but rather the result of a lower mass host, considering the mass-metallicity relation in galaxies. Based on observations of Milky Way star-formation and gas fractions for high redshift galaxies, we propose that a typical metal-poor GC with an original mass of $2 \times 10^6 M_\odot$ formed among a total cluster mass of $\sim 3 \times 10^7 M_\odot$ along with several $\times 10^9 M_\odot$ of dense gas and $\sim 10^7$ to $\sim 10^9 M_\odot$ of older stars. During a ~ 100 Myr burst phase when the star formation rate was several $M_\odot \text{ yr}^{-1}$, such galaxies would have AB magnitudes of ~ 26 and ~ 29 at wavelengths of $1.4\mu\text{m}$ and $3.3\mu\text{m}$ for $z \sim 2$ and $z = 6$, respectively, and the GCs would have magnitudes of ~ 34 to ~ 36 in this redshift range. The host dwarf galaxies would be ~ 1 kpc in size and subtend an angle of $\sim 0.15''$.

Lyman- α emitting galaxies are plausible formation sites for metal-poor GCs. They have the right size, luminosity, star formation rate, and metallicity. To determine whether LAEs also have the right space density to form all of today’s metal-poor GCs, we integrated the LAE luminosity function above $\sim 2.5 \times 10^{41} \text{ ergs s}^{-1}$, which is the expected Lyman α escape luminosity of a star-forming region that produces a typical GC today. This limit assumes an average 25% Lyman- α escape fraction and one magnitude of extinction for Lyman continuum radiation. The result equals the space density of today’s metal-poor GCs when corrected for the fraction of LAE galaxies that are in the active phase ($\sim 0.4\%$).

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